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Investigation of the Indoor Environment in a Passive House Apartment Building Heated by Ventilation Air

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KEYWORDS: *Low energy building, Passive House, warm air heating, thermal comfort, solar shading, field measurements, dynamic building simulation*

SUMMARY:
Experience has shown that appropriate design of very low energy dwellings can be a large challenge and that the final design may result in insufficient heating in winter and overheating in summer. The 126 certified Passive House apartments (Ravnsborghusene) in Køge, Denmark are a low energy building project finished medio 2012. The design challenge was met with a concept of air heating that is individually controlled in every room. It also applies external solar shading. This study used indoor climate measurements and dynamic simulations in one of these apartment buildings to evaluate thermal comfort and the performance of the air heating system and solar shading. Thermal comfort category B according to ISO 7730 was obtained in the building during field measurements, indicating that the air heating system was able to maintain comfort conditions in winter, when the outdoor temperature had been unusual low for a longer period. The dynamic simulations also indicated that air heating during winter can provide a comfortable thermal environment. Dynamic simulations also demonstrated that during summer, apartments with automatic external solar screens had no serious overheating, whereas in apartments with south oriented windows, static shadings by the balcony overhangs and low ventilation rates, resulted in excessive hours of overheating.

1. Introduction

From the Kyoto agreement in 1997 to the 2009 EU energy and climate package, the aim has been to reduce energy consumption of new and existing buildings. In the design of low energy buildings focus is to reduce the energy consumption. This may lead to design loads that are sensitive to variations in climatic conditions, user behaviour and changes during the building process.

The Passive House concept focuses on very low energy consumption for heating by efficient thermal insulation and utilization of the passive heat in the building. Here passive use of the solar load, occupants, electrical appliances etc. contributes considerably to heat up the space. Once the heating requirement is sufficiently low, the conventional water based heat distribution systems can be omitted and the dwelling heated by ventilation air alone. This may reduce the costs without compromising the indoor environment (Ellehauge et. al. 2008). However, recently published results found that poor design of air heating systems without individual control in each room and inadequate solar shading created problems with insufficient heating in winter and overheating in summer (Larsen 2011). These experiences from the first passive houses in Denmark have resulted in more detailed criteria on the space heating systems and on the performance of the indoor environment and namely thermal comfort. The current proposal for the future Building Regulations in Denmark, the current low energy class 2020, forbids the use of air heating alone and sets up concrete requirements for maximum acceptable indoor temperatures (Energistyrelsen 2013). But what if an air heating system is correctly dimensioned and gives occupants the possibility to control the room temperature individually and if the building has an effective, external solar shading? Would the thermal indoor environment then meet the best indoor climate category A? This study focuses on evaluating the air heating system and solar shading systems of a newly constructed low energy apartment building, based on field measurements and dynamic simulations. The studied apartments are part of 126 certified Passive House apartments (Ravnsborghusene) in Køge, Denmark which were finished medio 2012.

2. Building description

The investigated apartment building is one out of nine certified Passive House apartment buildings. Each apartment building consists of 14 apartments spread over an eastern and a western section (see FIG 1). The eastern section consists of four floors with four 4-room apartments and four 2-room apartments. The western section comprises six 3-room apartments divided into three floors. The gross area of the east and west section is 689 m^2 and 490 m^2, respectively.

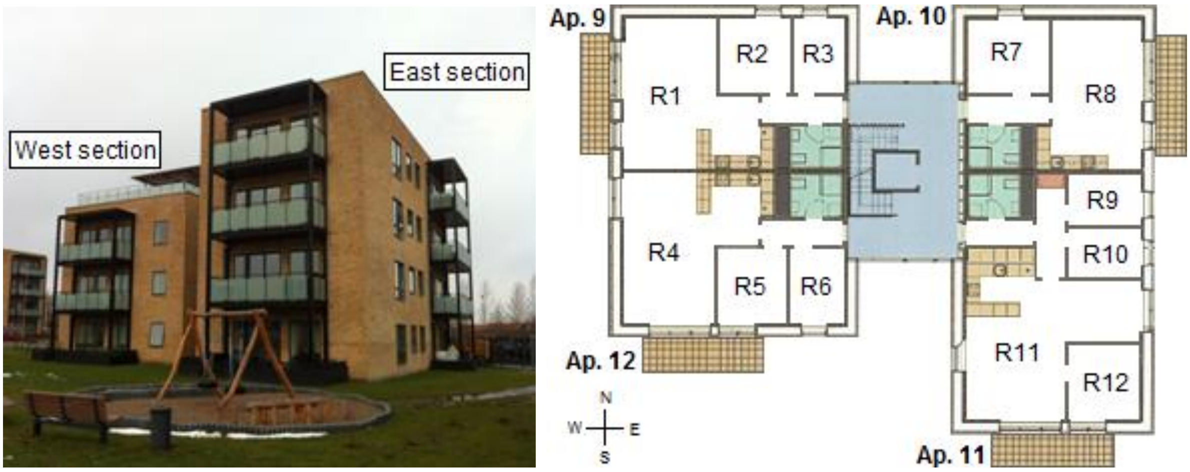

FIG 1. South east view of the investigated apartment building (left) and floor plan (right)

The apartment building is ventilated and heated by air from two centralized and balanced ventilation systems with heat recovery and pre heating coil. The supply air is heated by individual water based heating coils installed before each room inlet. The coil in each room can be individually controlled by thermostats. The heating system is based on three air to water heat pumps (AWHP) that supply heat to two domestic hot water tanks and a buffer tank. Automatic external solar screens are installed only at the east and west oriented windows. All 14 apartments have balconies towards east, west and south. These balcony overhangs operate as static shading.

3. Field measurements

3.1 Methods

Short and long term measurements were conducted to evaluate the thermal comfort and ventilation rates in the apartments.

3.1.1 Thermal comfort

Thermal comfort as well as local thermal discomfort was categorized according to ISO 7730 (2006), based on short term measurements. The purpose of the short term measurements was to evaluate if the air heating provided at specific locations in the living room was sufficient, during an unusual cold period where the outdoor temperature was approximately -8 °C. The average long term outdoor temperature in Denmark in January is -0.3 °C, the outdoor design temperature -12 °C and the design indoor air temperature is 20 °C. The short term measurements were conducted on January 25th 2013 in each apartment on the 2nd floor, at three locations in the living rooms R1, R4, R8 and R11 (see FIG 1). The selected locations represented the approximate positions where occupants would stay for long time periods. At each location air temperature, air velocity, plane radiant asymmetry and relative humidity were measured at the heights 0.1 m, 0.6 m and 1.1 m during a minimum period of three minutes. A clothing insulation value of 1.0 clo and a metabolic rate of 1.2 met were assumed to best represent the average occupants clothing and activity level. The ASHRAE comfort tool software was used to calculate PMV and PPD (ASHRAE55 2013).

3.1.2 Ventilation rate

Occupant generated CO_2 was used to estimate the ventilation rates by applying a single-zone mass balance (Bekö et. al. 2010). The CO_2 concentration was measured during a period of one week (January 25th 2013 to February 1st 2013) by a Vaisala CO_2 transmitter connected to a HOBO data logger with a built in air temperature and relative humidity sensor. The placements of the HOBO data loggers were in representative locations in rooms R1-R11 (see FIG 1). The data acquisition interval was set to five minutes. In order to smooth the data and reduce extreme values, a 20-minute running average was used. Individual activity protocols for each room were completed by occupants for each day, in order to obtain behaviour related input to the calculation of the ventilation rates.

3.2 Results

3.2.1 Thermal comfort

Air temperature, mean radiant temperature, relative humidity and air velocity were found for all measuring locations. The average values over three locations in each apartment living room are illustrated in FIG 2 together with their standard deviations. The measured air temperature was close to the mean radiant temperature which also coincides with the high surface temperatures measured at the floor and ceilings. This indicates uniform thermal conditions in the measured rooms caused by well insulated building envelope and inner walls creating individual thermal zones.

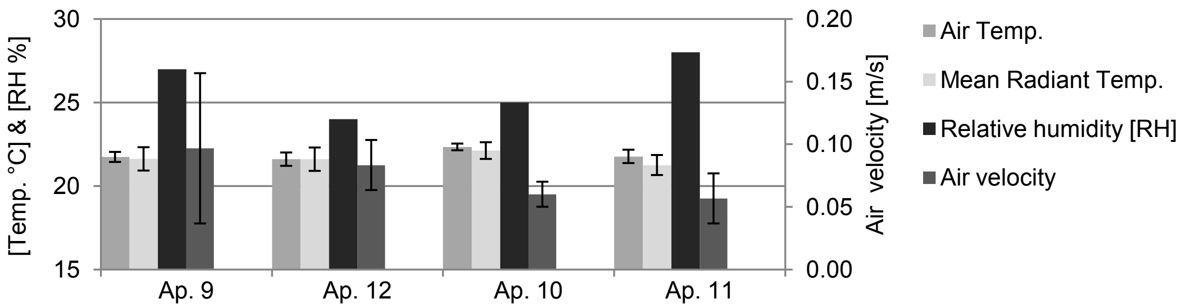

FIG 2. Parameters obtained in the 2nd floor apartments (Ap.9-12)

Based on the four obtained parameters and the assumed clothing insulation and metabolic rate, the PMV and PPD indices were calculated for the living room in each apartment shown in TABLE 1.

TABLE 1. PMV and PPD indices calculated for Ap. 9, 12, 10 and 11

Thermal comfort indices*	Ap. 9	Ap. 12	Ap. 10	Ap. 11
PMV [-]	-0.13	-0.13	0.04	-0.10
PPD [%]	5	5	5	6

*Calculation based on measurement at 0.6m height at three locations in each apartment living room.

According to ISO 7730 (2006), the PMV and PPD values for all apartments were within category A. In FIG 3, no noteworthy air temperature gradient occurred at any of the measurement locations. Also, the air velocity was generally below 0.15 m/s.

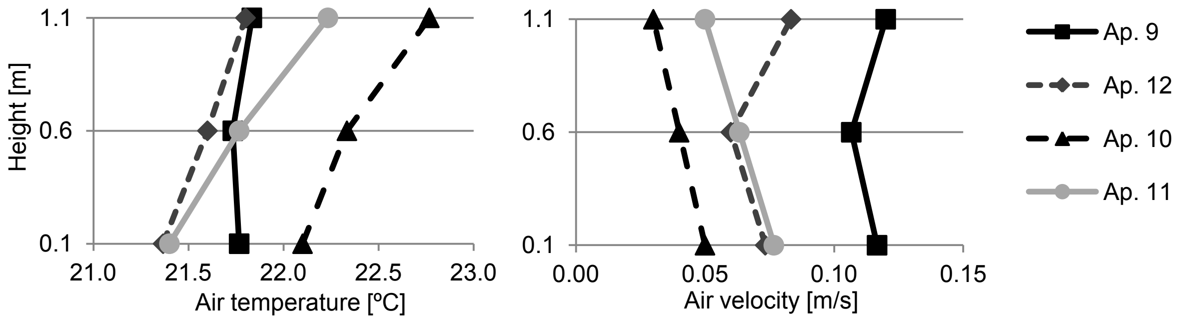

FIG 3. Vertical air temperature and air velocity profiles for the 2nd floor apartments

The local thermal discomfort measurements; draught rate (DR %), radiant asymmetry, vertical air temperature difference and floor temperature corresponded to category A for Ap. 12, 10 and 11, whereas Ap. 9 was in category B. The lower category was due to a slightly higher air velocity and lower air temperature, which resulted in 16 % draught rate.

3.2.2 Ventilation rate

In TABLE 2 the measured ventilation rates and the design values are shown. It can be seen that the measured ventilation rate, for most rooms, is comparable with the design ventilation rate. However, the ventilation rates for all rooms in Ap. 11 were much lower than the design values. The low ventilation rate in Ap. 11 may be due to the size and geometry of the apartment which created problems with sufficient ventilation or simply the fact that the ventilation system did not work properly for these rooms.

TABLE 2. Measured and design ventilation rates in the different rooms

Ventilation rates	Room [-]	Room Volume [m^3]	Measured* [l/sm^2]	Design [l/sm^2]
Ap. 9	R1/ R2/ R3	88.5/ 27.8/ 19.1	0.62/ 0.47/ -	0.6/ 0.7/ 0.7
Ap. 12	R4/ R5/ R6	88.5/ 29.8/ 19.1	0.72/ 0.63/ -	0.6/ 0.6/ 1.0
Ap. 10	R7/ R8	31.9/ 73.0	0.85/ 0.32	1.0/ 0.8
Ap. 11	R9/ R10/ R11	18.6/ 18.6/ 98.1	0.47/ 0.30/ 0.14	0.8/ 0.8/ 0.6

*The values are based on averages of the decay- and build-up periods throughout the measurement period.

4. Dynamic building simulation

4.1 Methods

The intended design of the heating and solar shading systems of the apartment building were evaluated by dynamic simulations performed with the simulation program IES- Virtual Environment, IESVE (IESVE 2013). The performance of the air heating and shading design was investigated throughout a one year period based on parameter variations. The parameter variations were compared with reference to the thermal environment categories I-IV given in EN 15251 (2007). The prerequisite for conducting parameter variations was to compare the simulated air temperature with measured data obtained from the HOBO data loggers during 25th of January 2014 to 1st of February 2014. The assumption was that if the simulated air temperatures approximated the measured ones, then the model setup would be sufficient in order to perform the parametric study.

4.1.1 Model setup

An IESVE model of the 2nd floor of the apartment building (see FIG 4) was set up, based on observations made during the field measurements and drawings of the building geometry. The rooms marked with black were included in the simulation while the grey ones were assumed adjacent rooms.

For the western apartment Ap. 9 and Ap. 12 additional heat loss is present compared to the eastern apartment.

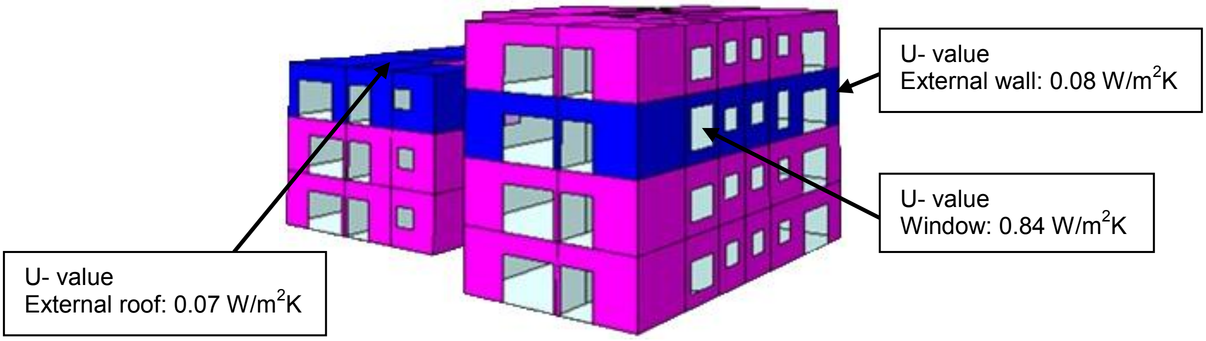

FIG 4. South east view of the IESVE model geometry of the apartment building and U- values

The location was set to Copenhagen/ Kastrup and the weather data file to 'CopenhagenDRY.ftw'. The automatic external solar screen system was set to roll down when the incident solar radiation was above 30 klx and to roll up again when it was below 25 klx. The static shading design from balcony overhangs had a shading angle of approximately 50°. According to fieldwork observations, internal curtains and vertical lamellas were included in Ap. 12 and Ap. 10.
Occupant and equipment profiles were created based on information provided from the activity protocols. The heat load emitted by the occupant was 90 W while the heat load from electrical appliances including illumination was approximated to 5 W/m^2 and 3 W/m^2 for the living rooms and bedrooms, respectively. The heat generated was assumed as 100 % sensible and 0 % latent. Venting was activated when the room temperature exceeded 26 °C during the occupied periods providing a venting rate of 0.9 l/sm² appropriate for manually operated windows (Aggerholm & Grau 2011). An overall infiltration rate of 0.07 l/sm^2 was estimated based on a Blower door test as a part of the Passive House certification ($n_{50} \leq 0.6$ h^{-1}).
The apartment building was ventilated and heated by a centralized Constant Air Volume (CAV) system with 85 % heat recovery based on two aggregates supplying the east and west sections. During the heating season, the heat exchanger was set to be active when the outdoor air temperature was below 15 °C and operated with a set point supply temperature of 18 °C. The heat exchanger was by-passed during the summer months when the outside temperature was above 22 °C. The individual heating coils installed before each room were set to regulate the air temperature as a function of the room air temperature. The coil adjusted the air temperature between 23 °C and 18 °C as the room air temperature varied.

4.2 Results

The results used for the evaluation of the model setup can be seen in FIG 5.

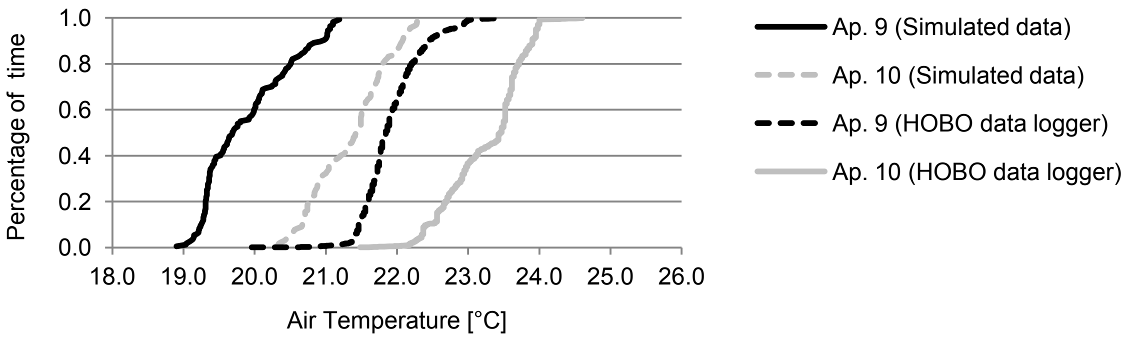

FIG 5. Simulated and measured air temperature distribution in Ap. 9 & Ap. 10 between 25th of January 2014 and 1st of February 2014.

The simulated and measured air temperature distributions ranged between 19-24.5 °C for the examined period (see FIG 5). In Ap. 9 the air temperature difference was approximately 2.5 °C where simulated temperatures were below 21 °C and measured ones mainly above 21 °C. In Ap. 10 simulated and measured data differed by 3 °C. In this apartment the simulated temperatures were below 22 °C and measured above 22 °C. The expected extra heat loss in the west apartment Ap. 9 and the air temperature difference between the apartments fit with both the simulated and measured air temperature distributions. The model setup was therefore considered sufficient to perform parameter variations where the intension was to compare the relative effect between different heating and shading designs.

4.2.1 Parameter variation

A parametric sensitivity analysis was conducted in order to evaluate the performance of the heating and shading system based on EN 15251 (2007). The parameter variations (P) are listed below:

- P1 was the reference model based on the intended model setup.
- P2 was similar to P1 but with a reduced supply set point temperature of 21°C, instead of 23 °C.
- P3 was similar to P1 but only with the balcony overhang as shading.
- P4 was similar to P1 but with added automatic external solar screens also on the south windows (controlled as the east and west windows).

To evaluate the air heating system the parameter variations P1-P2 were simulated. The results can be seen in FIG 6, where the annual thermal environment was compared.

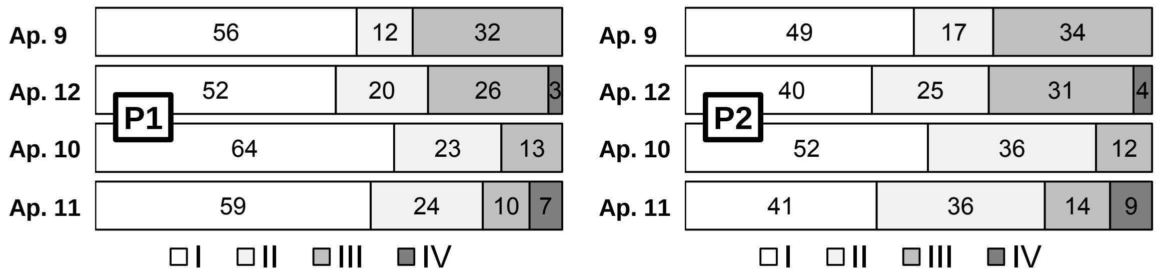

FIG 6. Annual thermal environment in % time in four categories for parameter variation P1 & P2

The reference model (P1) indicated a thermal environment within category III in Ap. 9, Ap. 10 and Ap. 12 whereas in the big south apartment (Ap. 11) 7 % of the occupied period was within category IV (see P1 in FIG 6). The reason for this was hours of overheating. When the supply temperature set point was reduced to 21 °C the occupied period within category IV increased 2 % (see P2 in Figure 6) and this was found to be caused by recorded hours below 20 °C as well.

To evaluate the influence of solar shading the parameter variations P3 and P4 were simulated and compared with the reference model (P1). According to FIG 6 the effect of the solar shading systems indicated that for P1 significant duration with overheating occurred in the South facing apartments (7 %). By removing the automatic external solar screens the duration of temperatures in category IV increased as illustrated in FIG 7.

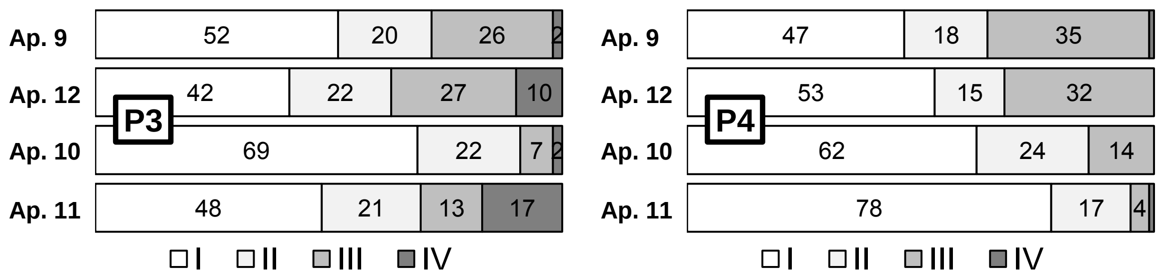

FIG 7. Annual thermal environment in % time in four categories for parameter variation P3 & P4

The design with no automatic external solar screens deteriorated the thermal environment in the living rooms with windows facing east and west, which in the actual case were the ones equipped with automatic external solar screens. This indicated that the design of the automatic external solar screens was effective in reducing the number of overheating hours. The apartment mostly affected was the large South oriented apartment (Ap. 11), where 17 % of the occupied period was within category IV. This was expected since it has a large glazing area facing south as well as windows oriented towards east and west. For apartments Ap. 9 and Ap. 10 with balconies facing east and west, the balcony overhang did not provide sufficient shading since the shading angle was designed for a high position of sun corresponding to summer midday (see P3 in FIG 7). Adding automatic external solar screens at the south windows of apartment Ap.12 and Ap.11, the number of hours with overheating was reduced significantly (see P4 in FIG 7).

5. Discussion

The results indicated PMV values within comfort ranges ($-0.2 < PMV < 0.2$) corresponding to the best indoor climate category A according to ISO 7730 (2006). Local thermal discomfort in Ap. 9 was within category B due to slightly increased draught rate. This showed that air heating alone with individual room control could maintain minimum thermal comfort category B in the apartments. The short term measurements also indicated uniform air temperature distribution as well as no air temperature asymmetry in the apartments where local discomfort could have been expected by the combined effect of heating by ventilation air and high measured ventilation rate.
Parameter variations illustrated that air heating was less sensible to change in supply temperature in the north apartments than in the south apartments, where a 2 °C lower supply temperature resulted in a 2 % increase of room air temperatures within category IV. Moreover parameter variations documented that automatic external solar screens were indispensable in order to achieve comfortable temperature ranges. The results also illustrated that the existing design can reduce overheating hours by 7-10 % in the south apartments. The simulations indicated that the design was likely to operate ineffectively during summer months as excessive hours of overheating were obtained in the south apartments even when venting was introduced. The simulation results should be validated in future work by performing field measurements during summer months while occupant observations is recommended to be taken into account by allocating questionnaires. By implementing automatic external solar screens to the south, thermal environment would improve further. However for dwellings this may constitute a problem since the user behaviour interacts with the shading control.

The ventilation rates in the apartment rooms were calculated based on the method of using occupant generated CO_2 to predict ventilation rate. The use of the single zone mass balance for estimating the air change rates does not take into account the distribution of CO_2 between rooms (interzonal air flow) and infiltration (Bekö et. al. 2010). The calculated air change rates could therefore be overestimated. In the current study the ventilation rates were calculated based on average values of decays throughout the measuring period. The consistency in well developed and continuing decays over the period increased the reliability of the estimated ventilation rate and provided a conservative measure for a total ventilation rate. In future work it is recommended to include airflow measurements at the air inlets or tracer gas measurements.

When performing dynamic building simulations uncertainties were involved as the indoor environment performance was estimated according to several assumptions regarding the schedule, occupant behaviour and heat loads. Fine tuning of the simulation model would be necessary in future work in order to comply with measured data. The intention of the dynamic simulation was to compare, based on a parametric study, the relative difference between temperature distributions. The results should therefore not be considered as absolute values since this would require a further validation of the simulation model and the use of specific located weather data.

6. Conclusions

Short term measurements documented that the provided heated air in the apartments could keep a minimum thermal comfort within category B according to ISO 7730 even in an unusual cold winter period. Using air heating with individual room control alone as well as higher ventilation rate can keep uniform operative temperatures without creating draught problems and is a sufficient mean of heating low energy apartment buildings.

Still an important factor to be considered for the design of low energy buildings is the correct implementation of external solar shading systems. This is possible by incorporating dynamic solar loads early in the design phase as static shading alone, caused by the balcony overhangs, cannot shade adequately the large south oriented windows. Building orientation, window distribution and dynamic shading need to be taken into account in order to utilize passive heating and still provide sufficient shading during summer.

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